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TITLE: COMPARISON OF STEAM-GENERATOR LIQUID HOLDUP AND CORE UNCOVERY IN TWO FACILITIES OF DIFFERING SCALE

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ABSTRACT

The Large-Scale Test Facility (LSTF) is a large-scale (1/48) integral-test facility built by the Japan Atomic Energy Research Institute for the study of pressurized water reactor (PWR) behavior during a small-break loss-of-coolant accident and reactor transients. Some of the LSTF experiments are intended to verify thermal-hydraulics phenomena that have been observed in the small-scale (1/1705) Semiscale test facility. Los Alamos National Laboratory and Idaho National Engineering Laboratory are using TRAC-PF1/MOD1 (TRAC) to analyze selected LSTF test runs.

Run SB-CL-05, a test similar to Semiscale Run S-UT-8, is a 5% break in the side of the cold leg. The test results show that the core was uncovered briefly during the accident and that the rods overheated at certain core locations. Liquid holdup on the upflow side of the steam-generator tubes was observed. After the loop seal cleared, the core refilled and the rods cooled. These behaviors were similar to those observed in the Semiscale run.

LSTF Run SB-CL-06 is a counterpart test to Semiscale Run S-LH-01. The comparison of the results of both tests shows similar phenomena. There was an early core uncovery just prior to loop-seal clearing when there was liquid holdup on the upflow side of the steam generators in both tests.

The similarity of phenomena in these two facilities builds confidence that these results can be expected to occur in a PWR. Scaling from Semiscale to the LSTF is a 35-fold increase in scale; this is almost halfway to full scale. One of the important phenomena is the steam-generator liquid holdup. Similar holdup has now been observed in the 6 tubes of Semiscale and in the 141 tubes of LSTF. It is now more believable that holdup may occur in a full-scale steam generator with 3000 or more tubes. These results confirm the scaling of these phenomena from Semiscale (1/1705) to LSTF (1/48).

The TRAC results for SB-CL-05 are in reasonable agreement with the test data. TRAC predicted the core uncovery and resulting rod heatup. The liquid holdup on the upflow side of the steam-generator tubes was also correctly predicted. The clearing of the loop seal allowed core recovery and cooled the overheated rods just as it had in the data.

The TRAC analysis results of Run SB-CL-05 are similar to those from Semiscale Run S-UT-8. In both runs there was core uncovery, rod overheating, and steam-generator liquid holdup. The ability of the TRAC code to calculate the phenomena equally well in the two experiments of different scales confirms the scalability of the many models in the code that are important in calculating this small break.

I. INTRODUCTION

Early core uncovery and heater-rod heatup were first observed in the Semiscale Mod-2a test facility in Run S-UT-8 (Ref. 1). These results were unexpected and further tests (S-LH-1 and S-LH-2 in Ref. 2) were conducted in Semiscale Mod-2c to study these phenomena. The Semiscale test facility is a small-scale (1/1705) model of a Westinghouse four-loop pressurized water reactor (PWR). It is composed of two loops, an intact loop representing three combined loops and a broken loop representing one loop. All of these tests modeled a 5% break in the cold leg. The analysis of the results showed that the early core uncovery was due to the manometric balance of pressures in the system (Ref. 2). The steam generated in the core cannot be vented until the loop seals clear. The pressure in the upper plenum and hot legs increases as the steam accumulates. The increased pressure causes the liquid level in the downflow side of the loop seal and the core to decrease. The liquid holdup on the upflow side of the steam-generator tubes increases the core level depression as the loop seal clears because it adds to the core side of the manometric balance. Figure 1 shows the manometric balance for S-LH-1 just prior to loop-seal clearing. If there were no liquid holdup, the core level would be depressed only to the level of the loop seal. Once the loop seal clears, the steam can be vented and the core is quickly recovered by the liquid that was in the loop seal. The manometric balance is reestablished between the downcomer and the core. The liquid holdup on the upflow side of the steam generator was due to the reflux cooling mode that had been established between the core and the steam generator, and to the counter-current flow limit (CCFL) in the steam-generator tubes. A second core uncovery may occur if the total system inventory is decreased by boiloff in the absence of the emergency core-cooling system (ECCS). This type of core uncovery is determined by a mass balance and is not the primary interest of this paper. This latter type of core uncovery is more important for the integrity of the core because of the long duration and the increased temperature attained by the rods. The small scale of the Semiscale facility (1/1705) was of concern in applying the Semiscale test results to PWRs.

The results of the Semiscale tests were described to the Japan Atomic Energy Research Institute (JAERI) and they were requested to investigate these phenomena further in the Large-Scale Test Facility (LSTF). The LSTF (Ref. 3) was built by JAERI and the test results are shared with the US Nuclear Regulatory Commission according to the terms of a bilateral agreement. The LSTF is a large-scale (1/48) integral-test facility for the study of PWRs during small-break loss-of-coolant accidents (SBLOCAs) and anticipated reactor transients. All the major components of the primary and secondary systems of a PWR are modeled by the LSTF. The LSTF consists of two loops, each representing two loops of the PWR. The steam generator modeling is very accurate for the primary side but on the secondary the tubes are 3 mm larger than in a PWR. The available power is limited to 14% of scaled full power, so that for steady-state operation the loop flow is reduced to maintain the correct temperature rise through the heated core. The secondary pressure is increased to reduce the primary-to-secondary heat transfer to 14%. The main objective of Run SB-CL-05 (Ref. 4) was to investigate the thermal-hydraulic mechanism of early core uncovery and heatup caused by manometric imbalance resulting from liquid holdup in the upflow side of the tubes of the steam generators.

Run SB-CL-06 (Ref. 5) is a counterpart test to Semiscale Run S-LH-1. The results show that the tests demonstrated all of the phenomena expected. The core uncovered briefly. Liquid holdup was observed in the upflow side of the steam-generator tubes. After the loop seal cleared, the core refilled and the heater rods cooled. Throughout the remainder of Run SB-CL-05, the core was cool, but in Run SB-CL-06 there was a second core uncovery and reheat caused by a boiloff of the system inventory.

The results of the Semiscale and the LSTF experiments are compared in this paper to show the similarity of the phenomena that produce early core uncovery at the two different scales of the facilities. TRAC-PF1/MOD1 (TRAC) (Ref. 6) was used to analyze one of the Semiscale and one of the LSTF tests. The comparison of the calculation and the experimental results on two different scales shows the ability of the TRAC code to calculate the phenomena and confirms the scalability of the many models in the code for calculating SBLOCAs.

II. COMPARISON OF THE RESULTS OF RUN SB-CL-05 TO RUN S-UT-8

Comparison of the behavior of Run S-UT-8 to Run SB-CL-05 shows very similar phenomena in both tests with some timing differences when these phenomena occurred. These timing differences occur because these two tests were not intended to be counterpart tests, so there are some differences in boundary conditions (mainly power level). Another significant difference is the loop modeling of the two different facilities. In the LSTF the two loops are equal and the loop-seal clearing occurs almost simultaneously in both the loops, whereas in the Semiscale, the intact loop that models three loops clears first and the broken loop clears later. The core uncovery was almost complete in both tests (Fig. 2). On the figure, the top of the core is - 130 cm and the bottom of the core is approximately - 500 cm. In response to the core uncovery, the cladding temperature at the center of one of the rods increased by 100 K (Fig. 3). The second core heatup in Run S-UT-8 is due to boiloff of the system inventory. Test SB-CL-05 had higher accumulator pressure, so the accumulator replenished the inventory before a second core heatup could occur. The loop-seal clearing and core recovery occurred in both the tests when the primary inventory was reduced to 30% of the initial inventory (Ref. 4). Run SB-CL-05 had higher core power so that the core uncovered earlier than run S-UT-8. The liquid holdup or delay in draining on the upflow side of the steam generator (Ref. 4) caused a pressure imbalance that was equivalent to 2.5 or 3.0 m of water (comparing the upside to downside levels in Figs. 4 and 5). The level measurements are referenced to the tube-sheet elevation.

III. COMPARISON OF THE RESULTS OF RUN SB-CL-06 TO RUN S-LH-1

Run SB-CL-06 is a counterpart test to Run S-LH-1, so the boundary conditions were chosen to duplicate those in Semiscale Run S-LH-1. Both tests show similar phenomena. There is an early core uncovery caused by the manometric pressure balance around the system and a second core uncovery because of the reduced system inventory (Fig. 6). The top of the core is −130 cm and the bottom of the core is approximately −500 cm. The early core uncoveries in the two test facilities are similar in magnitude and timing. The second core uncovery is less severe in the LSTF because of a larger ECCS flow such that the core did not uncover as much. The core level was decreased to about 1.0 m. The temperature heatups in the middle of one of the heater rods in each facility are compared in Fig. 7. The heatup in the LSTF is less than in the Semiscale, especially during the second core uncovery. The explanation of this difference is the reduced core uncovery during the LSTF test. The behavior in the steam generators is also similar in the two tests. Figures 8 and 9 show the upflow and downflow sides of the steam generator referenced to the tube-sheet elevation. The upflow side of the steam generators had liquid holdup during the period of the first core uncovery. The holdup was 1.0 to 1.5 m which is less than in Run S-UT-8 or Run SB-CL-05. The loop-seal clearing allowed the core to refill and cool after the first core uncovery.

IV. SCALING OF PHENOMENA

The important phenomena which led to the early core uncovery are the balance of pressures resulting from the inventory around the system, the core heat transfer, and steam-generator reflux cooling and CCFL. Both of the test facilities have the same elevations as a PWR so that the location and amount of the water in the system determine the manometric pressure balance. The heater cores of both facilities have the same geometry as a PWR. Only the number of heater rods has been reduced. The core heat transfer can be expected to be similar. The tubes in the steam generator are the same as those in a PWR. Only the number of tubes has been reduced. The steam-generator heat transfer and CCFL can be expected to be similar. The similarity of phenomena in these two facilities builds confidence that these results can be expected to occur in a PWR. Scaling from Semiscale to the LSTF is a 35-fold increase in scale, which is almost halfway to full scale. One of the important phenomena is the steam-generator liquid holdup. The holdup is dependent on the heat transfer and CCFL in the tubes. Similar holdups have now been observed in the 6 tubes of Semiscale and the 141 tubes of LSTF. It is now more believable that holdup may occur in a full-scale steam generator with 3000 or more tubes.

V. DESCRIPTION OF THE TRAC ANALYSIS OF RUN S-UT-8

The TRAC analysis results of Run S-UT-8 are briefly reviewed here (for details see Ref. 7) to compare with the TRAC calculation of Run SB-CL-05 to study the prediction of similar phenomena at two different scales. In the S-UT-8 experiment, there were two core uncoveries (Fig. 10). The early core uncovery is of interest because it is caused by liquid holdup in the steam generator and loop-seal clearing. There is reasonable agreement between the measured and predicted core levels. The calculated time of the first core-level depression is delayed by 25 s. The rod temperature response at the 208-cm elevation is shown in Fig. 11. There was limited heatup during the early core liquid level depression. The predicted temperature increase was in reasonable agreement with the data even though the first heatup was delayed 50 s. The delay in core depression in the calculation may have been caused by the slower mass loss out of the break (Fig. 12). The clearing of the loop seal occurs at the same mass loss. The collapsed liquid level in the upflow and downflow sides of the intact-loop steam generator is shown in Fig. 13. The liquid holdup or delay in draining on the upflow side of the steam generator is shown in both the data and the calculation. The level difference was 2.5 to 3.0 m. The calculated clearing of the steam generator and loop seal was delayed 50 s compared to the data. The second core uncovery and heatup due to the boiloff of the system inventory was also reasonably predicted by TRAC.

VI. DESCRIPTION OF THE TRAC ANALYSIS OF SB-CL-05

The next series of plots shows some of the comparisons between the TRAC calculation and the data (see Ref. 8 for more details). The reasonable agreement between the calculated and measured core differential pressures is shown in Fig. 14. Initially, there is excellent agreement, but as core voiding begins, the measured differential pressure decreases more rapidly than in the calculation. The core level is depressed until the loop seal clears and then the core is refilled rapidly. The slower calculated mass loss at the break explains the slower core-level depression in the calculation and the later refill as the loop seal clears (Fig. 15). The temperature response of one of the highest-powered heater rods is shown in Fig. 16. The measured and calculated temperatures at six axial locations are shown. The temperature follows saturation except for the short period between 140 and 180 s when the core uncovers and some rod locations heat up until the core refills and the rods are again cooled. There is moderate agreement between the data and the calculation. The calculated rod heatup is delayed, but the temperature increase is correct. Inspection of all the measured rod temperatures shows considerable variation form rod to rod within the core at any given elevation so that the agreement between the calculation and the data shown is typical of the average.

The steam-generator differential pressure measurement is divided into upflow and downflow sides of the tubes. The differential pressure instruments are connected to show a positive reading when the tubes are full of liquid. The comparison of the measured to calculated differential pressure for steam generator A upflow and downflow sides are shown in Figs. 17 and 18 respectively. Both sides show that the calculation begins draining the tubes earlier than the data, because of the lower initial temperature of the fluid in the upper head which voided first in the facility. After 80 s the agreement improves. Comparison of Fig. 17 to Fig. 18 shows that the downflow side drains at 100 s, while on the upflow side some liquid is held up and maintains a differential pressure of up to 30 kPa until the loop seal clears. The differential pressures for the loop B steam generator are similar to those for loop A. The loop seal differential pressure also is split in two sections. The downflow section connects the steam-generator outlet to the bottom of the loop seal. The upflow section connects the bottom of the loop seal to the inlet of the pump. The upflow and downflow side differential pressures for loop A are shown in Figs. 19 and 20, respectively. The downflow side (Fig. 19) begins clearing at the same time in both the data and the calculation, but the clearing proceeds more slowly in the calculation than the experiment. The upflow side (Fig. 20) clears after the downflow side.

The TRAC calculation of this experiment was in reasonable agreement with the data. TRAC predicted all the major trends and phenomena but was 20 s late in the timing. The predicted liquid holdup on the upflow side of the steam generator was in agreement with the data. The manometric pressure balance from the liquid holdup and loop-seal clearing caused the core to uncover and the rod cladding temperature to increase. After loop-seal clearing, the core recovered and cooled.

VII. SCALING OF TRAC MODELS

The ability of the TRAC code to calculate the phenomenon equally well in the two different volume scaled facilities confirms the scalability of the many models in the code that are important in calculating a 5% break.

VIII. CONCLUSIONS

The manometric pressure balance from the steam-generator liquid holdup and loop-seal clearing caused the core to uncover and the rod cladding temperature to increase. The clearing of the loop seal relieved the pressure imbalance and allowed the core to recover and cool. The similarity of results from Semiscale and LSTF confirms the scaling of the small-break phenomena observed in these experiments. The scale change from Semiscale to LSTF is 35 times, which is close to the 48-times scale change between LSTF and full scale. The reasonable agreement between the TRAC code calculation and the experimental data of two tests of different volume scales tends to confirm the scalability and accuracy of the small-break modeling in the code.

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8. F. E. Motley and R. Schultz, "Comparison of a TRAC Calculation to the Data from LSTF Run SB-CL-05," in Proceedings of the Fourteenth Water Reactor Safety Research Information Meeting (October 1986).

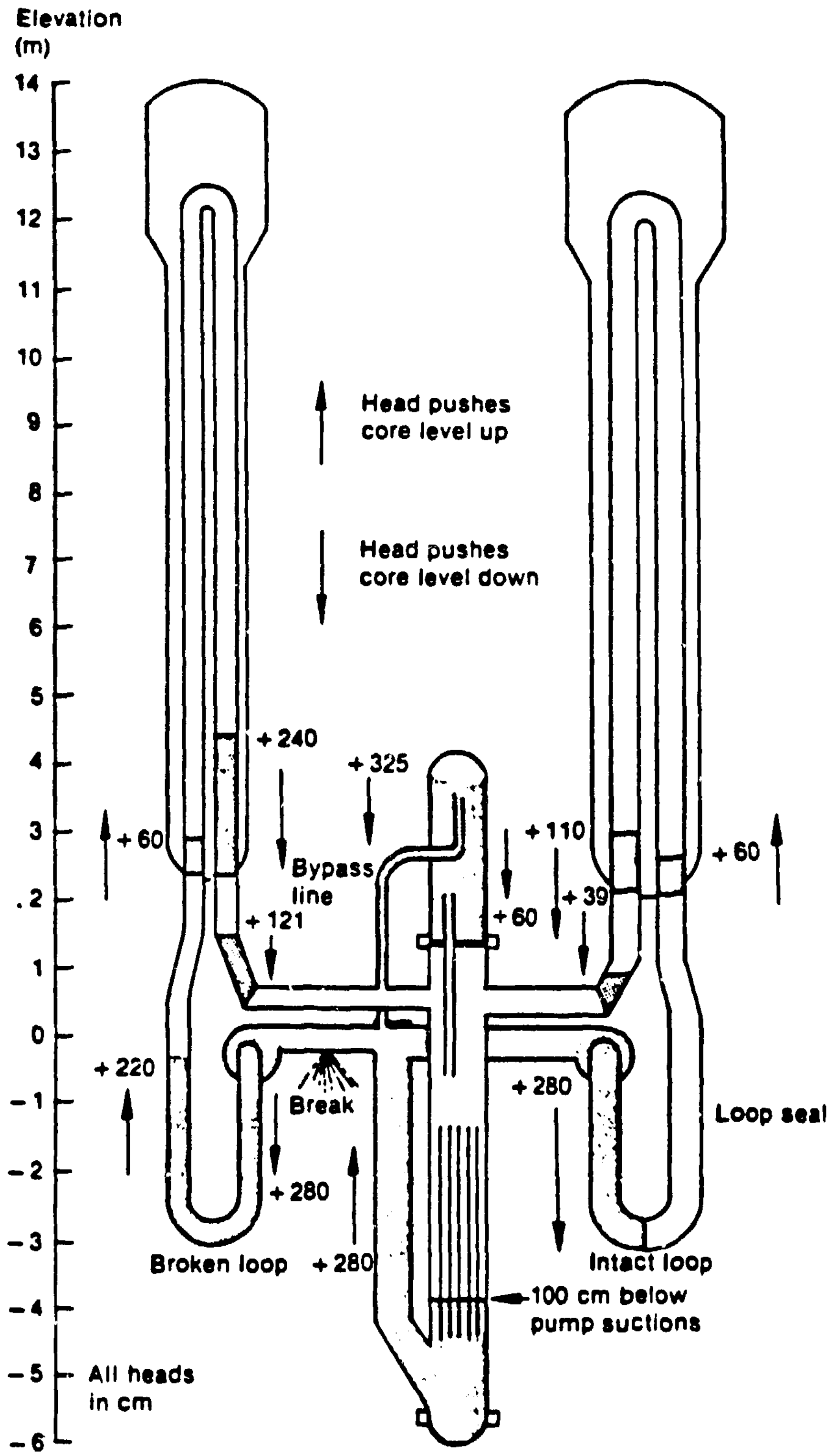

Fig. 1.
Manometric fluid head balance prior to intact-loop pump suction seal clearing during 5% SBLOCA Experiment S-LH-1.

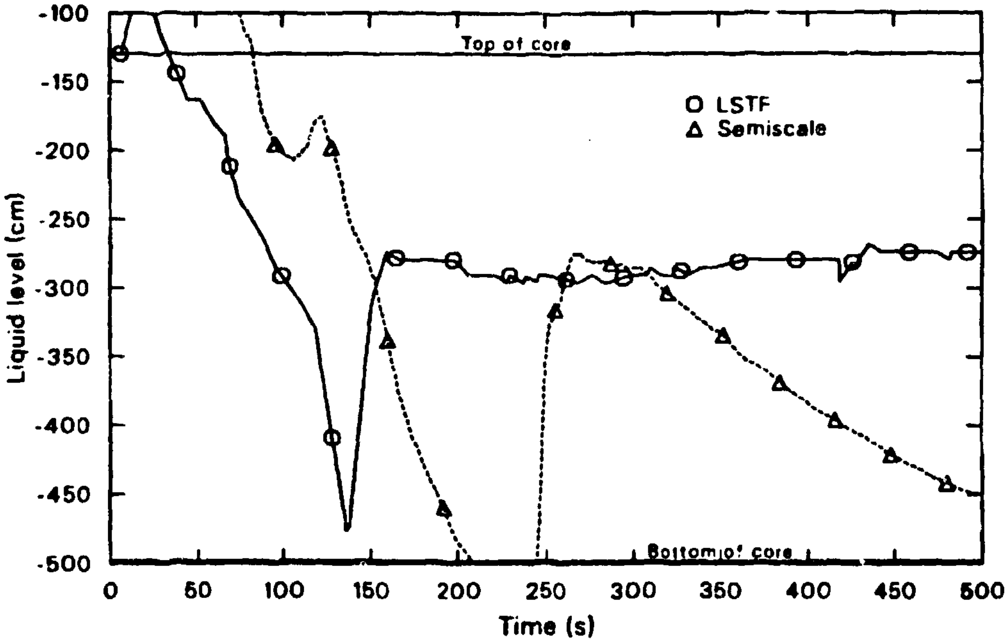

Fig. 2.
Comparison of the core levels in S-UT-8 and SB-CL-05.

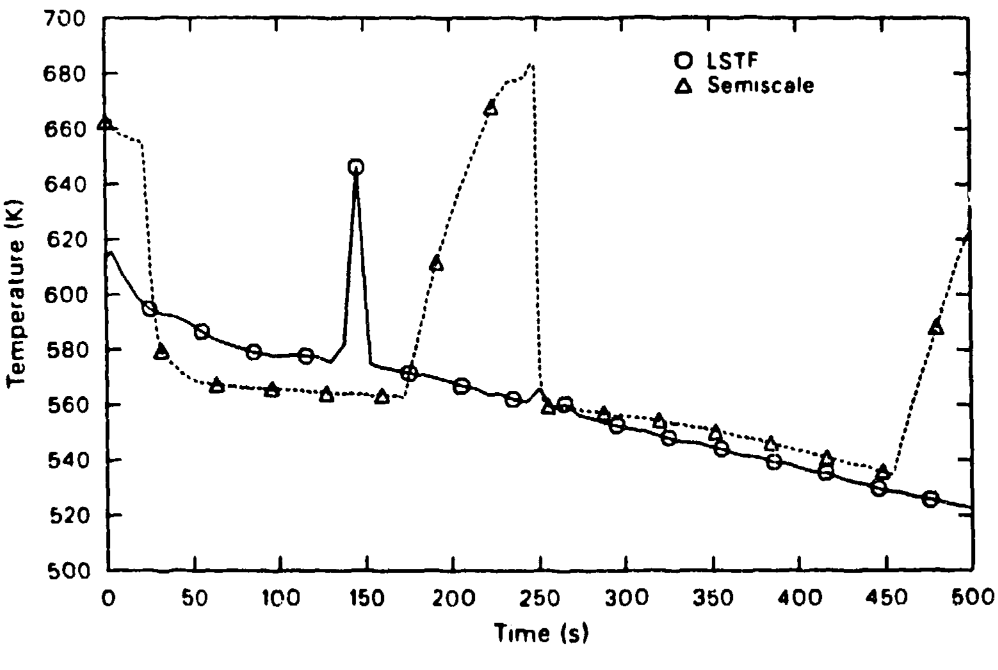

Fig. 3.
Comparison of rod temperatures at the 208 cm elevation from S-UT-8 and SB-CL-05.

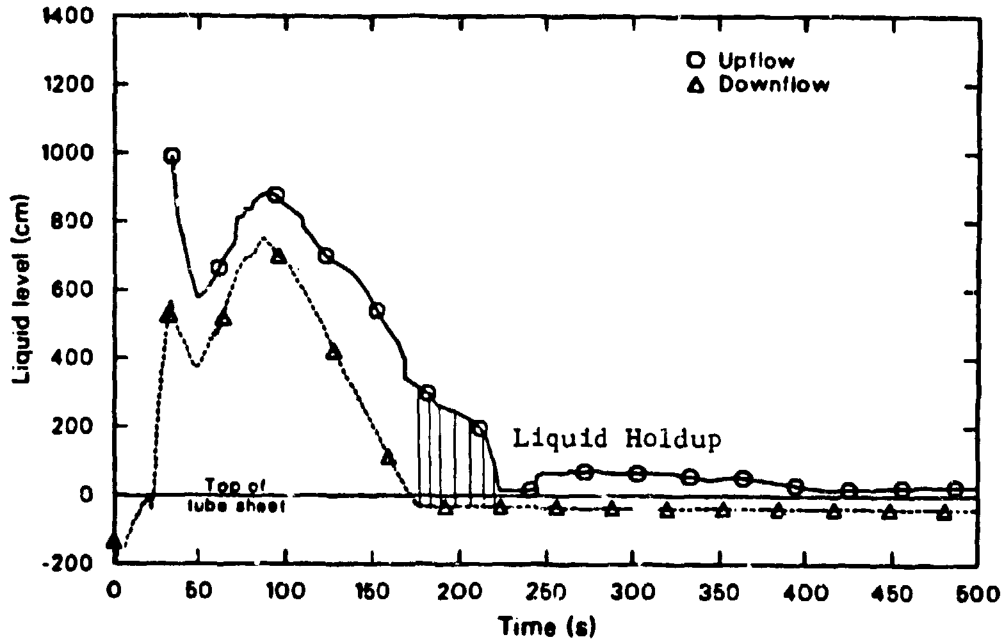

Fig. 4.
Comparison of the levels on the upflow and downflow side of the steam generator for S-UT-8.

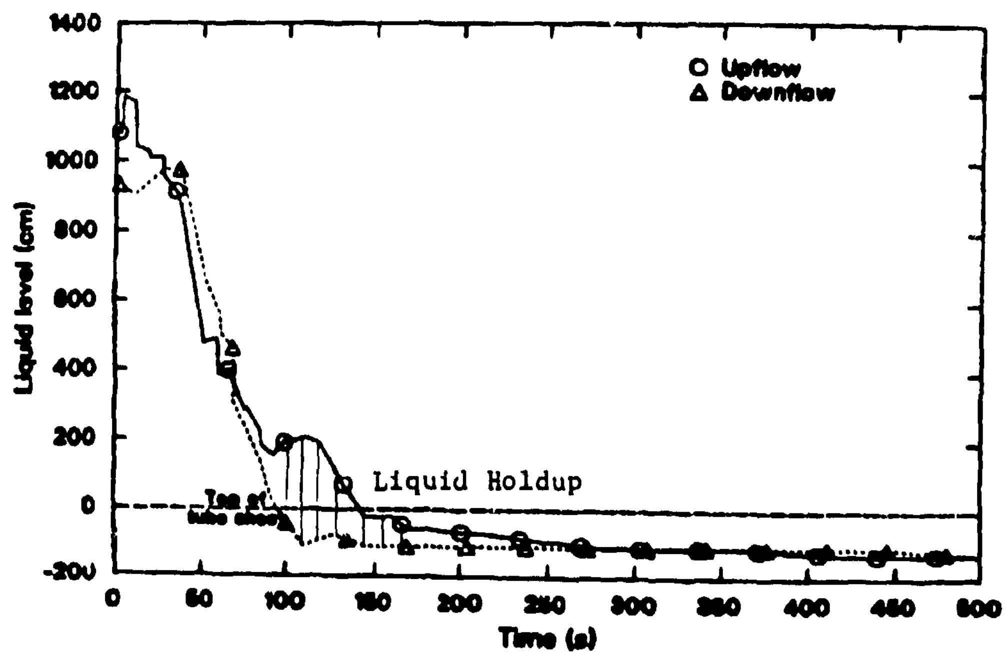

Fig. 5.
Comparison of the levels on the upflow and downflow side of the steam generator for SB-CL-05.

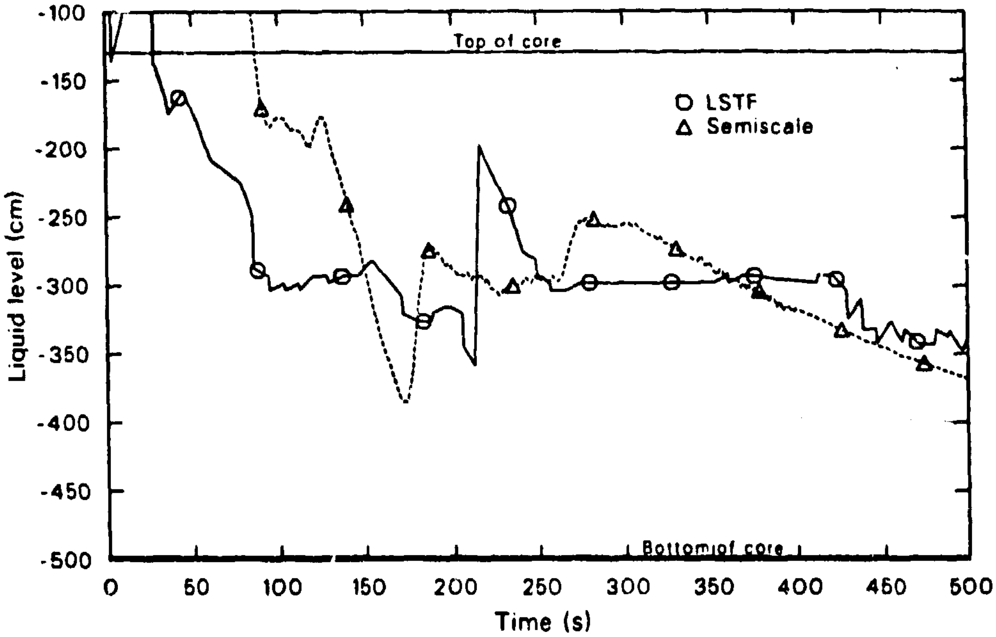

Fig. 6.
Comparison of the core levels for S-LH-1 and SB-CL-06.

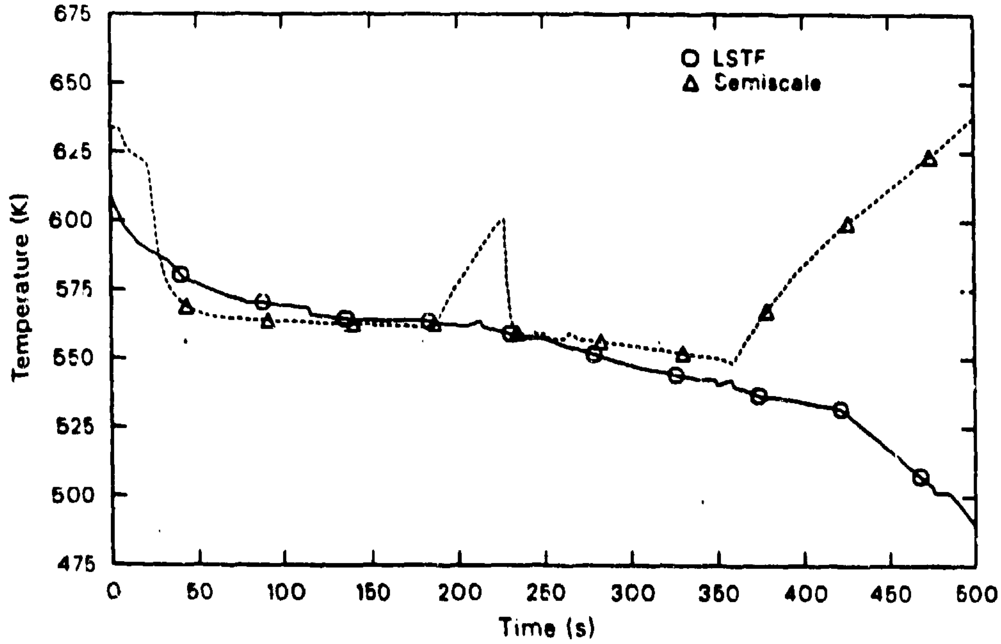

Fig. 7.
Comparison of the temperatures at the 208-cm elevation from S-LH-1 and SB-CL-06.

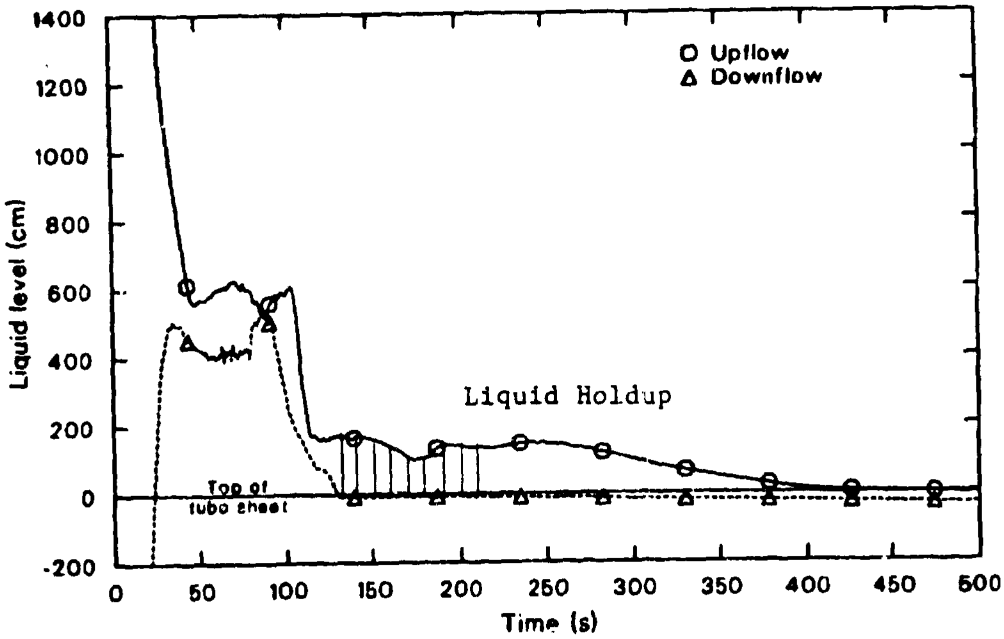

Fig. 8.
Comparison of the levels in the upflow and downflow sides of the steam generator for S-LH-1.

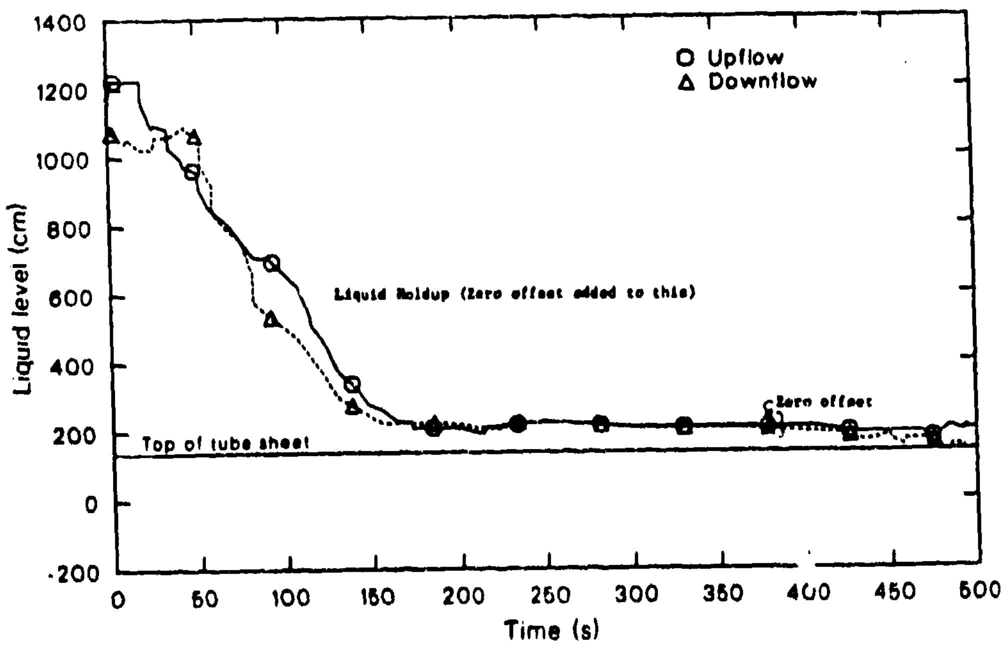

Fig. 9.
Comparison of the levels in the upflow and downflow sides of the steam generator for SB-CL-06.

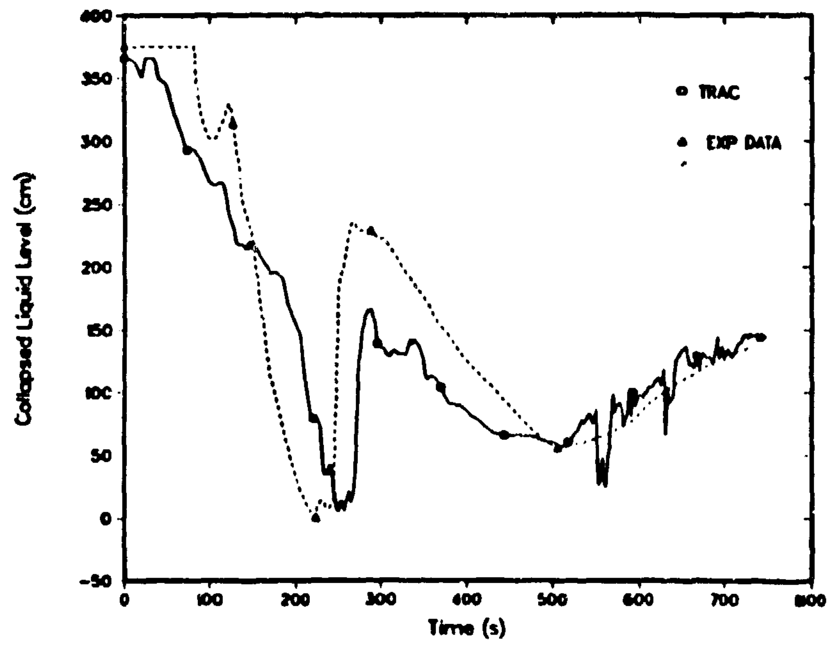

Fig. 10.
Comparison of TRAC-calculated (solid line) and measured (dashed line) core collapsed-liquid level.

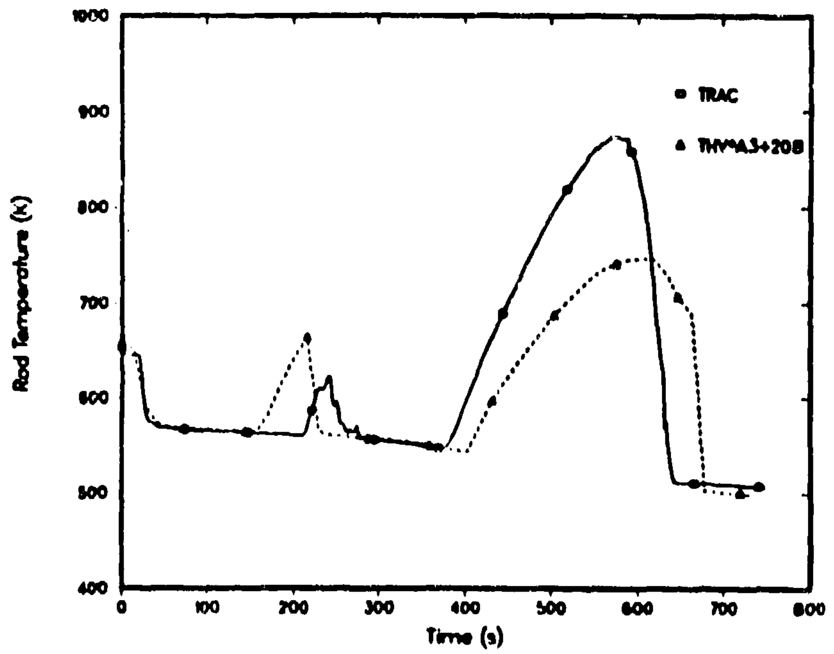

Fig. 11.
Comparison of TRAC-calculated (solid line) and measured (dashed line) heater-rod cladding temperatures at the 208-cm elevation.

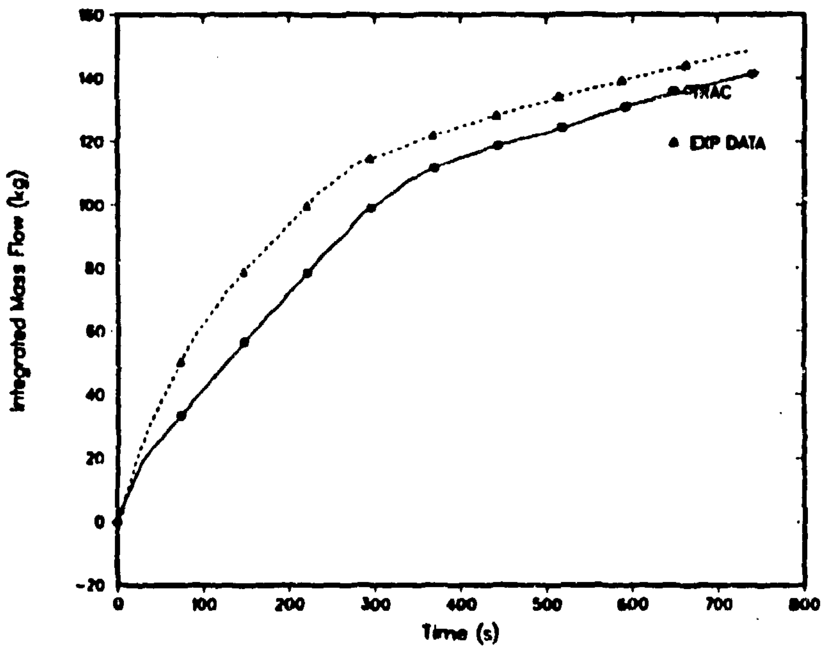

Fig. 12.
Comparison of TRAC-calculated (solid line) and measured (dashed line) integrated break mass flow.

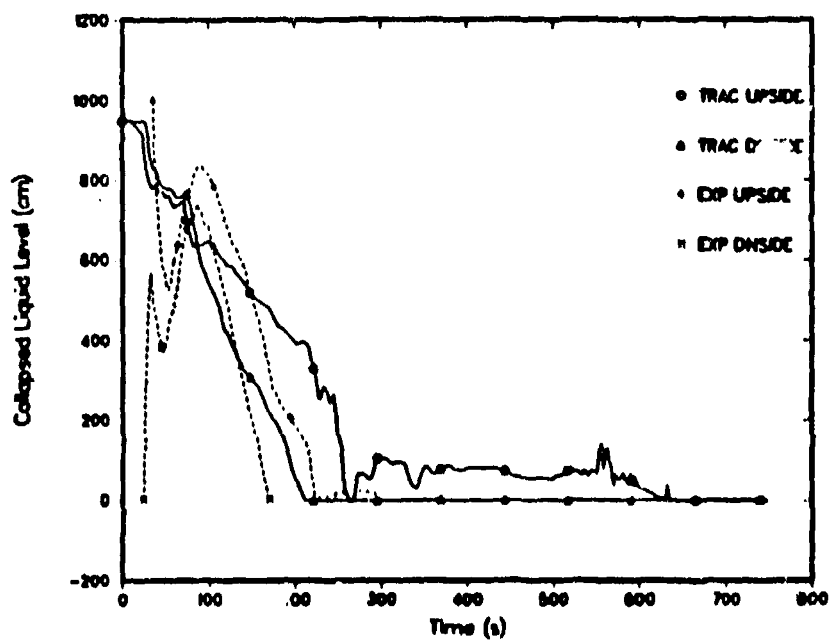

Fig. 13.
Comparison of TRAC-calculated (solid line) and measured (dashed line) intact-loop steam-generator collapsed-liquid levels.

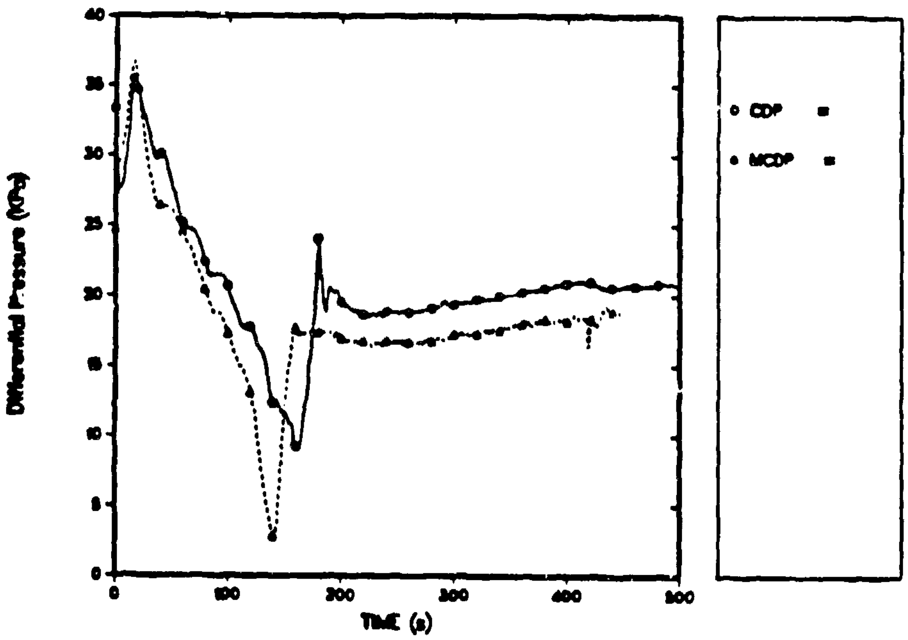

Fig. 14.
Comparison of TRAC-calculated (solid line) and measured (dashed line) core differential pressure.

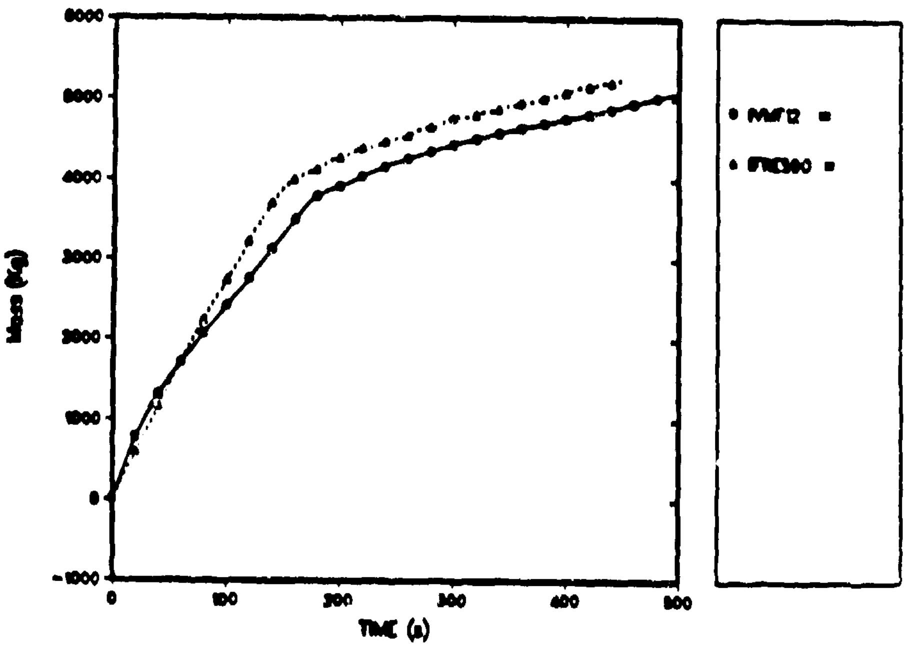

Fig. 15.
Comparison of TRAC-calculated (solid line) and measured (dashed line) mass loss out of break.

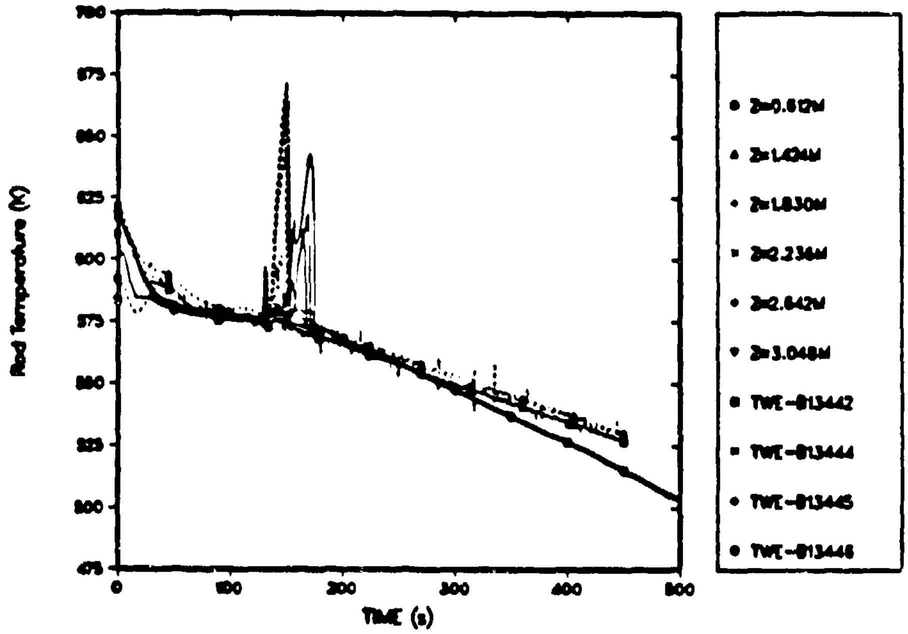

Fig. 16.
Comparison of TRAC-calculated (solid line) and measured (dashed line) rod-surface temperatures from bundle 13.

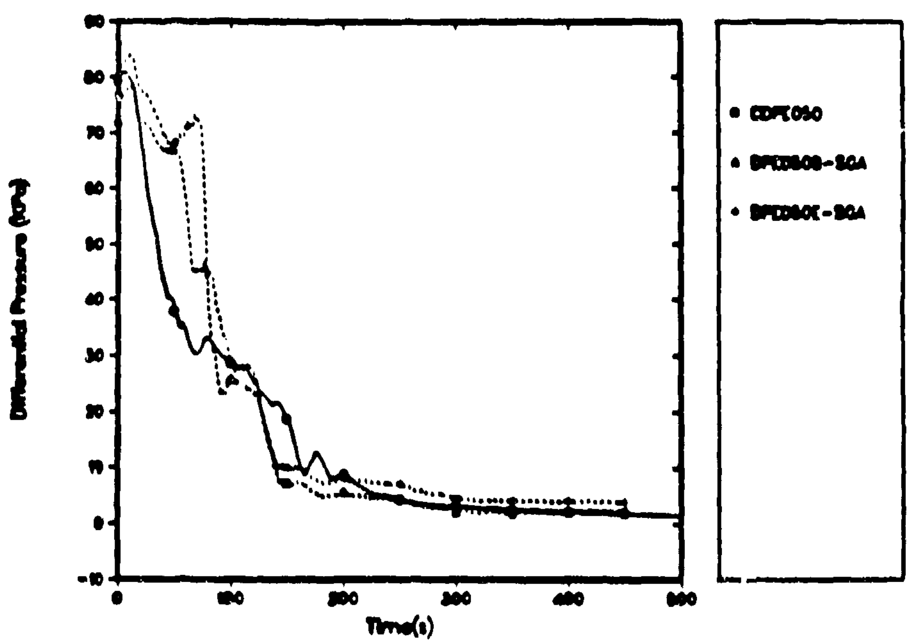

Fig. 17.
Comparison of TRAC-calculated (solid line) and measured (dashed line) Loop A steam generator upflow side differential pressure.

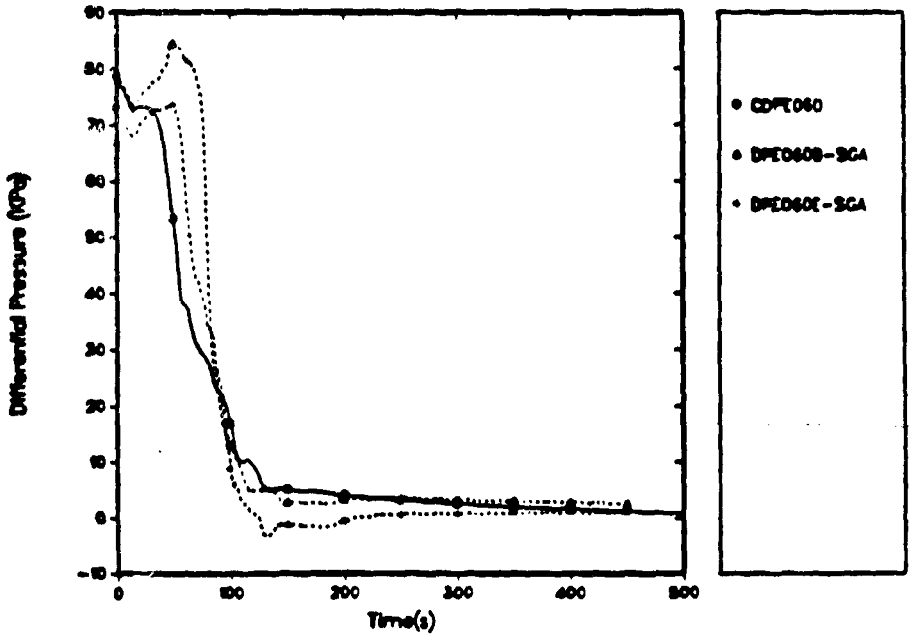

Fig. 18.
Comparison of TRAC-calculated (solid line) and measured (dashed line) Loop A steam generator downflow side differential pressure.

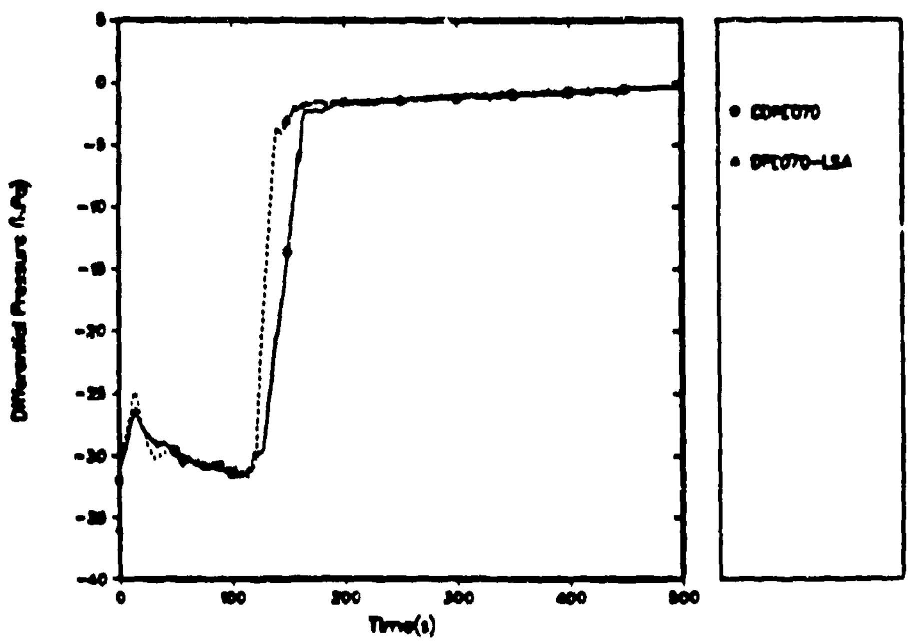

Fig. 19.
Comparison of TRAC-calculated (solid line) and measured (dashed line) Loop A loop seal downflow side differential pressure.

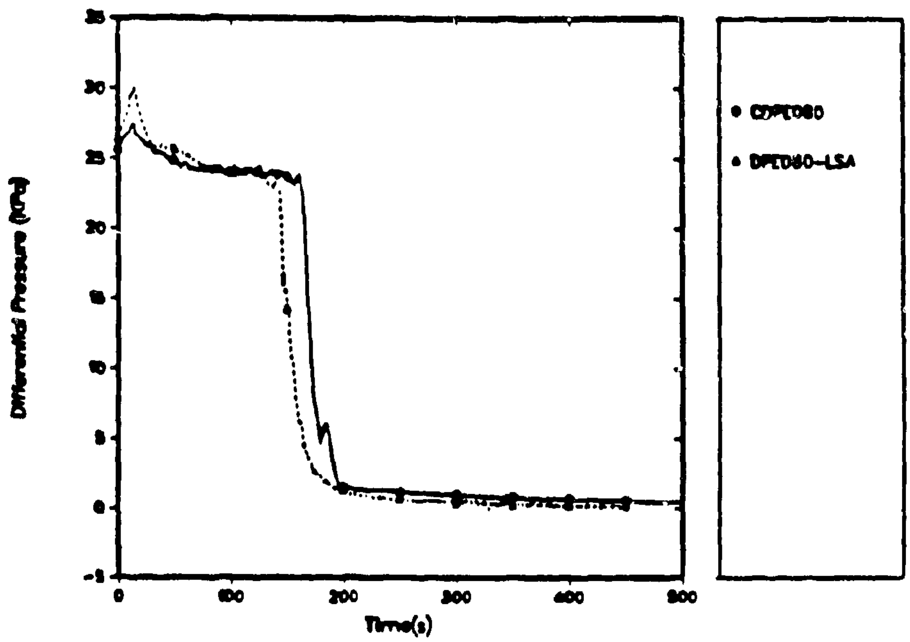

Fig. 20.
Comparison of TRAC-calculated (solid line) and measured (dashed line) Loop A loop seal upflow side differential pressure.